TRAVELING-WAVE AMPLIFIERS

LEE GEORGE CUTCHALL

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L. G. CHURCHILL

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by

Lee George Cutchall
Lieutenant, United States Navy

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PREFACE

This thesis is intended to familiarize the reader with the elementary principles of the traveling-wave tube and the associated problems. The scope will be confined to the use of a helix type slow wave circuit structure. Primary concern is higher gain with low added losses without oscillations. Conventional tubes commonly being used at present are discussed. A principle for the design of a new tube is proposed with theoretical possibilities and experimental measurements performed on a representative tube embodying this principle.

Appreciation is expressed to Dr. S. F. Kaisel of Stanford University who supervised the design and contributed valuable guidance. H. F. Poulter, of Stanford University Electronic Research Laboratory, was directly in charge of the physical construction and measurements. He aided immensely in many instances with the benefit of his personal experience with traveling-wave tubes. Much credit is also due to the men in the machine shop and tube department. Through their untiring efforts the tubes necessary to carry out the experimental work were fabricated.

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TABLES OF SYMBOLS AND ABBREVIATIONS

A — Loss relating voltage associated with the increasing wave to total applied voltage. Evaluated to be -9.54 db.

B (Gauss) — Magnetic flux density required to focus electron stream.

B — Gain constant depending upon attenuation added. Value of 47.3 with no loss and ignoring space charge effects.

C — Gain parameter, product of circuit impedance and beam impedance.

$\bar{E}$ — Electric field strength.

E — Peak electric field strength acting on the electron stream.

$\frac{E^2}{\beta^2 P}$ — Impedance parameter. Measure of circuit goodness as far as gain is concerned.

F (γa) — Function of product of radius of helix and propagation constant equal approximately to

$$7.154\, e^{-.664\, \gamma a} \quad \text{or}$$

$$F(\gamma a) = \frac{\left(\frac{E^2}{\beta^2 P}\right)^{\frac{1}{3}}}{\left(\frac{\beta}{\beta_0}\right)^{\frac{1}{3}} \left(\frac{\gamma}{\beta}\right)^{\frac{4}{3}}}$$

G — Traveling-wave tube gain, i. e. $\frac{\text{signal output}}{\text{Signal input}}$ expressed in db.

I_0, I_1, I_2; K_0, K_1, K_2 — Modified functions of γa in impedance equation

I_0 — Average electron convection current, d. c. beam current.

$\frac{I_o}{V_o}$ Beam admittance.

I^2R Power dissipated in added attenuation losses.

K Perveance $K = \frac{I_o}{V_o^{3/2}} \times 10^{-6}$

K_l Helix characteristic impedance defined on a longitudinal field basis.

K_t Helix characteristic impedance defined on a transverse field basis.

L Cold loss, added attenuation, expressed in db. Generally includes negligible insertion loss of helix. In some helices of very fine wire, this may be as high as 12 db and not negligible. These helices not treated herein.

N Axial length of tube in wave lengths.

i. e. $\frac{\text{axial length}}{\lambda_g}$ or $\frac{\text{length of helix wire}}{\lambda}$.

P Power flow in the helix circuit.

P_B Power in beam $I_o V_o$.

P_{mag} Power required to produce magnetic focussing field.

SWR Standing wave ratio.

V Voltage signal on beginning of helix.

V_o D. C. beam accelerating potential.

a Mean radius of helix.

b Radius of electron stream.

b_1 Relative velocity parameter.

c Velocity of light 3×10^{10} cm/sec.

d Diameter of electron stream $d = 2b$.

e 2.718.

f Frequency, cycles per second.

k Efficiency factor.

l Axial length of helix.

Δr Distance from helix.

r. f. Radio frequency.

u_o Average (d. c.) velocity of electrons in beam.

v Velocity (axial) of signal as progresses down the helix. Phase velocity of wave.

Δv Velocity deviation.

v_a Maximum velocity at which interaction with an electron stream of velocity u_o will occur.

v_b Minimum velocity at which interaction with an electron stream of velocity u_o will occur.

β Axial phase constant.

β_o Free space phase constant.

Γ Propagation constant.

ε Efficiency.

λ_g Wave length along longitudinal axis of helix.

λ_o Free space wavelength.

π 3.1416.

ω 2π frequency, i.e., angular velocity.

INTRODUCTION

In 1942 Rudolf Kompfner began work on a method to overcome the difficulties of a klystron operated as a high sensitivity amplifier at microwave frequencies. The chief difficulty which he sought to overcome was the transit time of electrons crossing the "working gap." It is by means of interaction with the electric field of the gap that the electron stream is energy modulated and also the amplified energy is recovered. The basic thought occurred that the energy transfer could perhaps be better effected if the electric field were traveling at approximately the same rate as the electron stream.

With this in mind, Kompfner constructed a structure to slow the electromagnetic wave to velocities corresponding to a reasonable accelerated beam voltage electron speed. He constructed a coaxial line with the inner conductor being a helix of such a pitch that the wave traveling around the helix at approximately the speed of light advanced axially at approximately the speed of the electron beam. With an experimental model he discovered that amplification resulted with a signal impressed on the helix and an electron stream projected down the axis. The electron stream velocity had to be properly adjusted or no gain was observed. He decided it was practical to use one length of helical line as a buncher and catcher combined. Thus a new tube, the traveling-wave tube, was conceived.[11] The conventional traveling-wave tube of today is constructed on the principle he discovered, with only minor improvements and modifications.

From this beginning, the traveling-wave tube was the subject of much work, study, and development. It was found to have application to amplification at microwave frequencies where use of conventional electron tubes was impractical. It was also found to produce gain over a very large bandwidth. A later discussion will expound the bandwidth characteristics. It may be compared to other high frequency amplifiers, the klystron and triode representing the best conventional tubes. (16) Both have the same fundamental limitations as to bandwidth capability. As the band is broadened at any frequency, the gain is decreased. There exists for any given tube a bandwidth beyond which no gain is available. This is due to the signal being applied by means of some sort of resonant circuit across the capacitance at the input of the tube. In the traveling-wave tube this limitation is overcome completely. There is no input capacitance nor any resonant circuit. The tube is essentially a transmission line with a negative attenuation in the forward direction. The bandwidth can be limited by transducers connecting the circuit of the tube to the source and load. This will be specifically discussed later. The tube also will have a change of gain with frequency, but this may be controlled by proper design. Thus, in a traveling-wave tube amplification is achievable at very higher frequencies and over extremely wide bandwidths. (16)

Conventional traveling-wave tubes are plagued by internal feedback as are other high gain amplifiers. This problem will be the primary concern of this thesis. Conventional type tubes which are currently being built are discussed and their characteristics, design parameters, performance, and limitations are treated. Present methods of oscillation

suppression will be discussed. An alternative method of preventing oscillations is proposed with substantiating experimental data obtained from a representative structure incorporating the principle. The advantages of lower power dissipation, higher forward gain, and lowered susceptibility to radical variations in individual tubes are pointed out.

CHAPTER I

THEORETICAL DESIGN CONSIDERATIONS IN CONVENTIONAL TUBES

1. General description of conventional traveling-wave tubes. (16) (7)

Referring to figure I, the basic components of a representative tube may be seen. Such a tube may be designed to operate with 20 to 20,000 volts accelerating beam voltage at frequencies from 50 megacycles to 100,000 megacycles. The input wave is transferred from the coaxial load to the helix by means of a matching coupler and a short pick-up platinum antenna. A molybdenum sleeve is fitted at the base of the platinum antenna for anchoring purposes. Similarly, the antenna at the output end radiates the amplified energy from the helix. The matching coupler is employed to effect the transfer of the energy output to a coaxial line. The electron gun is used to produce the electron stream which provides the source of energy similar to the plate supply in a conventional tube. The beam travels faster than the signal on the helix and imparts energy through interaction in being slowed down throughout the length of the helix. The collector is used to terminate the electron stream. The helix is used to slow the signal wave progression to approximately the speed of the beam. It will be noted that the gun anode, helix, and collector are all at a positive potential with respect to the cathode.(16) A means for focussing the beam is not shown. Using a parallel flow gun, a large coil conducting current, wound with the axis coincident with the tube, provides magnetic focussing. Due to increasing requirements, the higher powered tubes use Brillouin flow guns with resultant smaller focussing power and coils.(15)

Another very vital part of the tube not indicated in the figure is internal loss. High gains are experienced in the forward direction of the helix through interaction with the beam. Unless a nearly perfect match exists at the output coupler, the reflected wave along the helix will return to the input end in sufficient magnitude to sustain oscillations. If the tube is to be used as an amplifier, this feedback must be minimized. In conventional tubes a number of methods are in use, most popular of which is the addition of suitably shaped strips of aquadag on the interior or exterior of the envelope along the helix.[20] Aquadag is a lossy conductor which when placed in an electric field has induced current flow. Energy is dissipated in the form of I^2R losses. The principle objections to this are reduction of gain in the forward direction, reduction of efficiency, heat dissipation required, and the unpredictability of the amount of loss introduced. The optimum thickness of aquadag for loss introduction is inversely proportional to the distance from the helix and quite critical.[16] The conducting properties of aquadag change radically when subjected to heat such as occurs in final processes in tube fabrication. In the vacuum r. f. heating and outgassing, processes , the proper losses as measured previously may change greatly. Thus the tube may come out with excessive loss resulting in low output gain. Conversely, the loss may decrease radically, resulting in a tube which is completely useless.

A number of attempts to subject the properties of a helix to quantitative formulation have been made.[2][3][8][10][17][18] Many variables are involved and the interaction phenomena is quite complex. In order to have a theory simple enough to be useful, numerous simplifying assumptions must be made. All treatments make more or less restrictive assumptions

and obtain results which, though different in form, agree fairly well in predicted performance for any given set of parameters. In some cases, empirical formulation of experimental results is employed. Although nomographs, graphs, and equations exist in a great variety of forms,[4] no single standardized theory is accepted as explaining completely the action occurring. The bulk of effort in analysis has been concentrated on a small signal theory. A fairly satisfactory and reasonable formulation has been accomplished by a number of men working in the field. In general, no large signal theory has been promulgated.

2. Discussion of electric field and traveling-waves.[11][13][16]

Considerable work has been done to determine the configuration of the field associated with a helix. Most important is the magnitude of $\bar{E}$ which acts upon the electron stream. This is normally the longitudinal $\bar{E}$ on the axis of the helix for a solid small diameter beam. In large diameter helices a hollow beam may be employed, but for simplicity's sake, only the former case will be considered. The ratio of the square of the electric field to power flow has been evaluated by physical measurements even when it could not be calculated. C. C. Cutler did this by allowing the power from a waveguide to flow into a terminated helix, so that the power in the helix was the same as in the waveguide.[3] He then compared the field in the helix with the field in the waveguide by probe measurements. The field strength in the waveguide could be calculated in terms of power flow. Therefore, the field in the helix could be determined by comparison for a given power flow. The primary requirements of the $\bar{E}$ field for amplification interaction with the beam is that there be longitudinal

component along the axis. Cutler's plot of experimental measurements of relative field strength confirmed the presence of such a component in tubes which functioned as amplifiers. The magnitude of the $\bar{E}$ field on the axis as obtained by computation and experimental measurement is a function of frequency, being stronger for lower frequency.(2)

The field on the outside of a helix is also of interest, although for a different reason. At low frequencies the fields extend a greater distance outside the helix. This makes the suppression of low frequency oscillations feasible by the introduction of a collar of lossy ceramic around the tube. By proper distance location this ceramic may be quite effective on troublesome low frequencies, and not materially affect the higher frequencies in the designed band pass.(16)

Similar to a wave guide, a helix is capable of supporting many modes. The modes with which traveling-wave tubes are concerned are the transmission modes.(13) Reference to figure II shows the approximate instantaneous charge distribution on helices for the simple modes. The lowest transmission mode has adjacent regions of positive and negative charge separated by many turns. This mode is readily applicable to the traveling-wave tube since the adjacent regions of positive and negative charge are separated by an appreciable axial distance, giving rise to a substantial longitudinal $\bar{E}$ field component parallel to the axis at the center of the helix. The requirements as to spacing and circumference relationships are shown in figure III.

One thing which nearly all small signal analyses bring out is the presence of four waves to explain the resulting phenomena.(2)(8)(14)(17)(18)

From a study of Laplace transforms it is known that two circuit elements such as L (and/or R) and C result in a second degree equation. The beam and the helix are the equivalent of four elements resulting in a quartic. The analysis reveals the first wave is an increasing wave (negative attenuation) which travels slightly slower than the electrons of the beam. The second wave is a decreasing one (positive attenuation) which travels more slowly than the electrons of the beam. The third wave is unattenuated, and travels faster than the electrons. The fourth wave, unattenuated, is a backward wave which travels in a direction opposite to the beam. The combination of these waves, with their proper amplitudes, phase relationships, and velocities of propagation give the resultant picture from which overall gain and other quantities are predicted. For high gain amplifiers the first wave is of such magnitude that the others by comparison are negligible.

3. Helix impedance.(16)

No impedance has yet been formulated which gives full information for matching a helix to a transmission line. In the case of transducers between a coaxial line and a waveguide, or between waveguides of different cross-section, the impedance is important but so are discontinuity effects. A suitable defined helix impedance is of interest as a relative quantity for comparison and relation to other physical quantities previously discussed.

Figure IV presents the impedance as defined on a voltage-power basis. The "transverse" characteristic impedance, K_0, is defined by the relation

$$P = \frac{1}{2}V_0/K_0$$

the impedance is found to be given by

$$\left(\frac{\beta}{\Gamma}\right)\left(\frac{\beta_0}{\beta}\right)K_t = \frac{120\, I_0^2}{(\Gamma a)^2}\left[\left(1+\frac{I_0 K_1}{I_1 K_0}\right)\left(I_1^2 - I_0 - I_2\right) + \left(\frac{I_0}{K_0}\right)^2\left(1+\frac{I_1 K_0}{I_0 K_1}\right)\left(K_0 K_2 - K_1^2\right)\right]^{-1}$$

The I's and K's are modified function of argument Γa. The dashed line on figure IV is a plot of $\frac{30}{a}$ vs Γa. For large values of Γa

$$K_t = \left(\frac{\beta}{\beta_0}\right)\left(\frac{\Gamma}{\beta}\right)^2 \frac{30}{\Gamma a} = \frac{c}{v}\frac{30}{\Gamma a}$$

Also, using a longitudinal voltage, another impedance may be defined. Since

$$V_l = \frac{\Gamma}{\beta} V_t$$

then

$$K_l = \frac{\Gamma}{\beta} V_t$$

The impedance parameter $\frac{E^2}{\beta^2 P}$ is twice the longitudinal impedance.

The transverse voltage V_t is greater than the longitudinal voltage V_l because of the circumferential magnetic flux outside the helix. For slow waves, $V_l = V_t$. Then the circumferential magnetic flux is small compared with longitudinal flux inside of helix. For very fast waves, longitudinal voltage becomes small compared with the transverse voltage.

4. Gain and bandwidth considerations. (19) (16)

Gain and bandwidth are so closely related that they will be discussed here in conjunction. Many of the variables and physically controllable design parameters are closely related to both. In designing a tube it is generally necessary to compromise for best combined results rather than optimizing one and allowing the other to suffer.

Certain relationships, although basic, are stated here for sake of clarity

$$\beta_o = \frac{\omega}{c}$$

$$\beta = \frac{\omega}{v}$$

$$\beta^2 = \beta_o^{\,2} + \tau^{\,2}$$

but for $v \ll c$ $\qquad\qquad\qquad\qquad$ $\beta = \tau$

Originally it was believed that a highly desirable circuit property for wide bandwidth was constancy of phase velocity, v, with frequency. In order to produce gain, the circuit phase velocity must be near the electron stream velocity. Efforts in design were constantly toward minimizing the deviation of v with frequency. This resulted in large values of τa, the product of the propagation constant, τ, and the helix radius, a. Using this criterion, considerable difficulty was experienced in obtaining high gain, i. e., in excess of 20 db. without a great deal of oscillation at frequencies remote from the designed center frequency. It was then discovered that by using a small value of τa, high gain with a narrow bandwidth and freedom from remote frequency oscillation could be achieved.[12] The small values of τa were classified as dispersive. There is no sharply defined line dividing dispersive from nondispersive helices. Robinson and Kompfner established a criterion of

$$\tau a = \frac{2\,\pi\,a}{\lambda_g} \leq 1.2 \qquad (12)$$

Robinson in a separate article set this boundary at 2.0.[19] A dispersive helix is characterized by the velocity of the wave supported varying rapidly with frequency. Since

$$\tau a = \frac{\omega\,a}{v} = \frac{2\,\pi\,f\,a}{v}$$

then

$$v = \frac{f\,(2\,\pi\,a)}{\gamma\,a}$$

It can be readily seen that for small values of γa, v will depart from v center frequency more rapidly than it would for large values of a for a given value of a. Use is made of the dispersive property to restrict the electronic bandwidth, i. e., the bandwidth over which velocities are compatible for beam wave interaction to occur. By use of this design, the bandwidth is restricted to a degree which it is easily possible to produce couplers having a very low reflection coefficient. Thus oscillation tendency is reduced within the desired band as well as outside. The sacrifice in bandwidth can be as large or small as desired. This design allowed the construction of a 3000 megacycle tube, 1600 volt beam voltage with a bandwidth of 200 megacycles and stable gain of 25 db. Thus it was possible, due to the narrow band and good matching couplers (over such a narrow band) to use only the insertion loss of the wire in the helix, some 12 db., and obtain stable gain as great as 30 db.[19] This tube, however, lacks the flexibility of operating over a wide range or being used for broadband work. Also, attempts to achieve higher gain would require better couplers or added losses. Figure V is an approximate frequency-gain characteristic plot for specific values, indicating the rapid decrease of gain off center frequency in the dispersive region. Figure VI is a similar plot indicating the existence of a γa in the dispersive region which gives maximum flatness for a symmetrical band of frequencies. Another important advantage of the dispersive traveling-wave tube is that the beam current required to obtain a given gain is reduced. As a result tubes in the dispersive region are much less noisy.

Another interaction circuit for which phase velocity of the growing wave is made to coincide with the beam velocity over a narrow frequency range only is created by the use of an external "filter helix."(5) A circuit of the type desired, wherein phase velocity is fairly uniform over a narrow frequency band and changes rapidly outside this band, behaves like a band pass filter. The uniform helix is in general a wide band structure. An iterated filter network with repetitive impedance discontinuities is a narrow band circuit. Making use of a nondispersive helix with an external surrounding helix containing such discontinuities as sudden changes in pitch, a narrow band structure may be constructed in which the band pass region may be shifted by changing the filter helix. This appears highly desirable as it increases the flexibility of a single tube. The process of changing filter helices might entail retuning and adjustment of beam voltage. In general it would be still more desirable if a tube could be produced with a wide bandwidth in which oscillations did not occur and artificial losses were not required. This principle makes the narrow band operation more flexible than resort to dispersive helices.

Now let us see how gain can be computed. A number of graphs, parameters and approximations are involved.(4) (7) (16) The most universally used equation is

$$G = A + BCN$$

BCN is the gain which a tube would have assuming only the increasing wave present and the beam already in a bunched condition at the beginning of the helix. A is a constant negative quantity calculated to be -9.54 db. It is largely to compensate for the gain not obtained at the first part of

the helix while the beam is being bunched. B is taken as 47.3 with no loss and ignoring space charge effects. Now

$$C = \left(\frac{E^2}{\beta^2 P}\right)^{\frac{1}{3}} \left(\frac{I_o}{8 V_o}\right)^{\frac{1}{3}}$$

The circuit part of C is measured by the cube root of an impedance, $\frac{E^2}{\beta^2 P}$, which relates the peak E acting on the electron stream, the phase constant, and the power flow. $\left(\frac{E^2}{\beta^2 P}\right)^{\frac{1}{3}}$ is a measure of circuit goodness as far as gain is concerned. To obtain high gain, it is desirable to have a circuit with a high impedance parameter. It is also desirable to have a high beam admittance, $\frac{I_o}{V_o}$. For a given helix $\frac{(E^2)}{(\beta^2 P)}^{\frac{1}{3}}$ is approximately proportional to F (γa) which empirically is approximately $7.154e^{-.664 \gamma a}$.

Since

$$\gamma a = \frac{\omega}{v} a$$

F(γa) decreases as frequency increases. Physically this is because at high frequencies (short wave lengths) for which the sign of the field alternates rapidly with distance, the field is strong near the helix but falls off rapidly away from the helix. Hence, the field to interact with the beam is weak at the axis because of the more rapidly curved path of the $\bar{E}$ lines for short wave lengths. The charge distribution in figure II can be visualized as being compressed axially, so that $\bar{E}$ does not protrude as far toward the axis. The $\bar{E}$ field strength at the helix surface decreases with frequency also. At very high frequencies the field falls off away from the helix approximately as $e^{-\gamma \Delta r}$ where Δr is distance from the helix. If Δr is infinitesimally small, with γ being directly proportional

to frequency, it can be seen that the electric field strength is proportional to $e^{-f\frac{(\gamma \Delta r)}{v}}$. Therefore, $\bar{E}$ becomes weaker at the boundary with higher frequencies and decays more rapidly toward the axis. N is the number of wave lengths along the axis. It is directly proportional to frequency since, at higher frequencies, λ becomes shorter, making N increase with frequency.

A summary of this should point up the reasons for the inherent broad band characteristics of a traveling wave tube.(1)(16) As phase velocity deviates from electron velocity the interaction is not as strong, thus tending to decrease gain both above and below center frequency. The allowable range of velocity deviation at which gain can be realized is of the order of

$$\Delta v = \pm C u_o$$

Thus, the allowable difference between the phase velocity of the circuit and the velocity of the electrons increases as circuit impedance and beam current are increased for a fixed beam voltage. The gain is proportional to F (γa) N. N increases with frequency while F (γa) decreases with frequency, due to weaker $\bar{E}$ on axis. These two factors, the $\bar{E}$ field becoming weaker at the axis decreasing C, and the number of wave lengths increasing, tend to balance each other and extend the bandwidth. Thus, traveling-wave tubes are inherently broad band devices.

5. Beam voltage considerations.

The choice of V_o, the beam accelerating potential is quite important. It is very closely related to the length of the helix, gain, focussing power required, and power capability. To demonstrate the relationship, representative or optimum values are assigned to γa, b/a and fo. The center frequency of 3000 megacycles is chosen because problems at this

frequency are representative of a wide band extending downward to 500 megacycles and upward to 48000 megacycles. A ratio of

$$\frac{b}{a} = .7$$

is selected. This is a practical figure, being large enough to obtain sufficient power in the beam, yet not so large as to make helix current excessive. The value of 1.8 is assigned γa. The constant, γ, is inversely proportional to $V_o^{1/2}$. Thus the helix radius, a, must be directly proportional to $V_o^{1/2}$ to maintain a constant. The value of 1.8 represents approximately the best gain-frequency characteristics. Computations indicate this value gives the maximum symmetrical flatness.

a. <u>Determination of B (gauss) required for Brillouin Flow as a function of V_o</u>

Using the constants as selected and two graphs, i. e., figure VII "Beam Current vs Beam Voltage with Perveance, K, as a Parameter and Constant Beam Power Contours" and figure VIII "Magnetic Field for Brillouin Flow with Perveance K as a Parameter", the values of B_{gauss} can be determined. Representative values of 1, 10, 25, 50, 100, 500, 1000, 5000 watts beam power are used. Using figure VII, the Beam Voltage, V_o, and Perveances are recorded for a fixed power. Then using this V_o and K, the product Bd, where d is diameter of beam, is obtained from figure VIII. The value of d is computed. Since

$$\gamma a = \frac{\omega}{v} a = 1.8 \qquad \frac{v}{c} = \frac{V_o^{1/2}}{506}$$

$$1.8 = \frac{2\pi\, 3x10^9 a}{V_o^{1/2}\, c/506} = \frac{2\pi a}{V_o^{1/2} \frac{1}{50.6}}$$

$$a_{helix} = \frac{1.8\, V_o^{1/2}}{50.6/2\pi} = .00567 V_o^{1/2}$$

$$\frac{b}{a} = .7 \qquad d = 2\,b$$

With the known diameter of beam, B_{gauss} is determined by dividing the Bd as determined graphically by d as computed.

It is also possible to formulate mathematically the B_{gauss} required for focussing with Brillouin flow. (15) Beginning with

$$B_{gauss} = \frac{1660}{d} K^{\frac{1}{2}} V_0^{\frac{1}{2}}$$

$$K = \frac{I_0 \, 10^{-6}}{V_0^{3/2}}, \quad P_B = I_0 V_0$$

Substituting,

$$B_{gauss} = \frac{1660 \, I_0^{\frac{1}{2}} \times 10^{-3} V_0^{\frac{1}{2}}}{.000795 \, V_0^{\frac{1}{2}}} \qquad \frac{1660 \times 10^{-3} \, P_B^{\frac{1}{2}}}{.00795 \, V_0^{5/4}} .$$

Thus for fixed P_B, $B \propto 1/V_0^{5/4}$. It is apparent from this, and also from curves, figures VII and VII, that for low B_{gauss}, values of V_0 should be as high as practicable. Physically this signifies that a weak highly accelerated beam is most easily focussed. For a plot of B_{gauss} vs V_0 with constant P_B and K contours for constants selected, see figure IX.

b. <u>Determination of required length as function of gain, beam voltage, perveance and power</u>

Now it is desired to find how the power, perveance, and beam voltage affect the required length of the tube. As previously,

$$G = A + BCN$$

In this equation, experiment and theory indicate that A, the db loss required to bunch the beam is the order of 10 db. A value of 25 is chosen for the constant B. Pierce predicted B = 47.3 for no loss or space charge. However, if an average amount of loss is added to decrease the oscillation tendency, and space charge is accounted for, the value of B decreases to a representative figure of 25. Of course, this can be varied by the amount of losses introduced.

Now

$$\left(\frac{E^2}{\beta^2 P}\right)^{\frac{1}{3}} = \left(\frac{\beta}{\beta_0}\right)^{\frac{1}{3}} \left(\frac{\Gamma}{\beta}\right)^{\frac{4}{3}} \left[F(\gamma a) \cdot \text{Correction factor for Solid Beam}\right]$$

There are a number of other methods of formulating the $F(\gamma a)$ X $\left[\begin{array}{l}\text{Solid Beam}\\ \text{Correction Factor}\end{array}\right]$ but all lead to approximately similar numerical results. The graphs in Pierce's book, "Traveling-Wave Tubes," are used in this method.[16]

Also,

$$\frac{\beta}{\beta_0} = \frac{c}{v} \qquad \frac{\Gamma}{\beta} \approx 1 \quad \text{for } v \ll c$$

$$\left.\begin{array}{l} F(\gamma a) = 2.3 \\ \text{Solid beam corr. factor} = 1.2 \end{array}\right\} \text{Graphs by Pierce}$$

$$\left(\frac{E^2}{\beta^2 P}\right)^{\frac{1}{3}} = \left(\frac{c}{v}\right)^{\frac{1}{3}} (1)\ (2.3)\ (1.2) = \frac{506\ \ (2.3\ \ (1.2)}{V_0^{\ \frac{1}{6}}} = \frac{22}{V_0^{\ \frac{1}{6}}}$$

$$C = \left(\frac{E^2}{\beta^2 P}\right)^{\frac{1}{3}} \left(\frac{I_0}{8\ V_0}\right)^{\frac{1}{3}} = \frac{22\ I_0^{\ \frac{1}{3}}}{2\ \ V_0^{\frac{1}{6}}\ V_0^{\ \frac{1}{3}}}$$

$$N = \frac{l}{\lambda_s} = \frac{l c}{\lambda_0 v} = \frac{506\ l}{10\ \ V_0^{\ \frac{1}{2}}}$$

$$G = -10 + 25 \times 11\ \frac{I_0^{\ \frac{1}{3}}}{V_0^{\ \frac{1}{2}}} = \frac{50.6\ l}{V_0^{\ \frac{1}{2}}}$$

$$\frac{(G + 10) \qquad (V_0)}{25 \times 11 \times 50.6 I_0^{\frac{1}{3}}} = \quad = \frac{(G + 10)\ V_0}{13900\ I_0^{\ \frac{1}{3}}}$$

Now, by assigning values to gain in db and using values of I_0 and V_0 as obtained from figures VII and VIII, l can readily be computed. To obtain a short l, it is desirable to have a large I_0 and small V_0. These conditions are met when perveance is high (power fixed) and beam voltage low, giving high current density. That a low V_0 is desirable to obtain small l can

further be demonstrated by substituting for I_o.

$$l = \frac{.0144 V_o V_o^{1/3}}{P_\beta^{1/3}}, \quad \therefore l \propto V_o^{4/3}$$

For a plot of l vs V_0 with constant P_B and K contours for the constants selected, see figure X.

c. <u>Optimum length-focussing power conditions</u>

The conclusions of (a) and (b) establish opposing trends of V_o for B_{gauss} and l. For a fixed power, the larger V_o, the smaller B_{gauss} required. However, for small l, low V_o is required. Thus it might be expected that a proper choice of V_o and K for a fixed power would yield minimum combined B_{gauss} and V_0. However, since $B_{gauss} \propto NI$, with fixed N, $B^2_{gauss} \propto I^2$; $I^2 R = P_{mag.}$; therefore $I^2 \propto P_{mag.}$ and also $B^2 \propto P_{mag.}$ Using as a criterion the product of magnetic power required and the helix length, by substituting it is seen that

$$B^2_{gauss} l = \left(\frac{1660 \times 10^{-3} P_\beta^{1/2}}{.00795}\right)^2 \cdot \frac{.0144 V_o^{4/3}}{P_\beta^{1/3} V_o^{1/4}}$$

$$B^2_{gauss} l \propto \frac{1}{V_o^{1/6}}$$

This indicates if focussing field power and length considerations are of equal importance, that the maximum possible available voltage should be used. A plot of B^2_{gauss} l vs V_c showing constant P_B and K contours, is presented in figure XI.

6. Power output and efficiency.(7)(16)

When an electron beam is shot through the helix, the electrons are accelerated or decelerated by the field of the wave, especially the longitudinal E field. As a result the beam electrons will be bunched. Because of the bunching action, there will be, in time, more electrons decelerated

than those accelerated over any cross section or vice versa. As a result there will be a net transfer of energy from the beam to the wave, or from the wave to the beam. During amplification the electron beam behaves like a generator with negative conductance, supplying power to the fields through a net loss of kinetic energy by the electrons.

As long as the discussion is limited to low level r. f. power throughout the tube, the assumption of a constant electron velocity u_o is valid. The energy transferred from the electron beam to the r. f. field will be a negligible fraction of the total kinetic energy of the electrons. The electron beam initially moves at a higher velocity than the interacting wave. As the individual electron progresses along the tube it loses more energy in deceleration than in acceleration. The average electron velocity will decrease slowly at the beginning but will decrease rapidly toward the end since r. f. power level increases exponentially. Assuming a long lossless helix, maximum energy exchange occurs if the beam enters with a velocity v_a corresponding to the upper end of amplification range and leaves with velocity v_b, corresponding to the lower end of interaction range. Maximum efficiency of energy conversion is

$$\epsilon = \frac{v_a^2 - v_b^2}{v_a^2}$$

For a typical tube the upper limit is from 10% to 25%.[2]

A theoretical evaluation of power output requires a theory of the non-linear behavior of the tube. At the present time the power capabilities and efficiencies attainable in practice leave considerable to be desired. One thing appears clear from both theory and experiment;

the gain parameter C is important in determining efficiency. It was previously seen that v_a and v_b were dependent upon C. Maximum efficiency is proportional to C by a factor k which varies as velocity parameter b_1. Hence

$$P_{out} = k\, C I_o V_o$$

For an electron velocity equal to unperturbed wave, efficiency is equal to 3C. Thus if C is .25, efficiency is 7.5%. However, if C is increased to .1, which is physically attainable, efficiency should equal 30%.(16)

Experimental efficiencies are found to be very low. Three reasons may explain the cause of lowered efficiency. First, small nonuniformities in wave propagation set up new wave components which extract energy from the increasing wave. The excitation of parasitic modes lowers power output. Second, theoretical assumption that the a-c field is constant on all electrons in the beam does not hold. Electrons more remote from the helix are acted upon less favorably by the $\vec{E}$ field. Third, conventional tubes have a central lossy section followed by a relatively short output section. Such tubes may be overloaded so severely in the lossy section that a high level in the output section is never attained. There is not enough length of loss free circuit to provide sufficient gain so that the signal can build up to maximum amplitude from a low level increasing wave. Other tubes with distributed loss suffer because the loss cuts down the efficiency.

If at a given frequency, I_o is increased, V_o held constant, both input power and efficiency should increase. Since C varies as $I_o^{1/3}$ by changing current alone, $P_b \propto I_o^{4/3}$. Also, at a given voltage, current,

and C, the efficiency increases as the diameter of helix is decreased. However, as the helix diameter is made smaller, it is necessary to decrease I_o and optimum gain occurs at higher frequencies.

The helix was at one time believed not to be adaptable to large power outputs. Instead, periodic structures, such as baffle loaded coaxial structures, which conducted heat better than the helix were studied.(6)(9) However, helix type tubes are being built with increasingly higher powers in both the pulsed and cw outputs. The heat dissipative properties of the helix are being worked on to improve the power capabilities.

7. Cold loss required in conventional tube.(16)(19)

Fundamentally, artificial attenuation is required in helix type traveling-wave tubes because of the difficulty in securing reflectionless helix terminations over the extremely wide amplification band of this type of tube if the Γa is large. It is generally assumed that, at some point in the helix amplification band, nearly complete reflection will occur at both couplers. To prevent reflections from resulting in regenerative oscillations, such devices as dispersive helices and filter helices are resorted to. They limit the amplification band and simplify the coupler requirements. However, with sufficiently high gain, due to coupler limitations (coefficient of reflection being too high) oscillations again become of concern. Likewise, with nominal gains in broad band helices, since compromise of higher coupler coefficient of reflection has been made in exchange for wider bandwidth, oscillations are a problem both within the assigned band pass and outside where amplification, though decreased, still exists (as velocity is still compatible with beam velocity) but a very high coupler coefficient of reflection exists.

To prevent reflections from resulting in regenerative oscillations, attenuation is introduced. In general, attenuation is introduced that exceeds the net gain of the tube. This condition is found to automatically prevent oscillations at any other frequency for which terminal reflections are large because lowered forward amplification generally accompanies departure from designed center frequency.

The subject of added loss and the effect upon output gain should be considered in more detail. First consider the criteria for oscillation. The incident signal will be amplified in the forward direction by an amount of G. This is the G from the equation

$$G = A + BCN$$

The G is the actual amplification realized i. e., voltage output/voltage input. The B to be substituted in the equation is approximately 25 as found experimentally by gain measurements on stable tubes. For oscillations to occur (refer to figure XII) the signal starts at (1), is increased by G in the forward direction and at (2) a fraction of this is reflected. The signal is diminished by L in the reverse direction and reflected again at (1). If the overall gain of this loop is unity or greater, oscillations will occur.

As an illustrative example assume that a SWR of 2.0 exists at both input and output couplers. This can be achieved with little difficulty over a wide band. Now,

$$SWR = \frac{1 + ke}{1 - ke} = 2$$

$$2(1 - ke) = (1 + ke)$$

$$ke = \frac{1}{3}$$

Assume a forward gain of 40 db is desired. This is equivalent to a

voltage gain of 100.

Hence,

$$100 \times \frac{1}{3} \times L \times \frac{1}{3} = 1$$

$$L = \frac{1}{11.1} = 0.09$$

$$L \text{ db} = -21 \text{ db}$$

or

$$40 - 9.56 - L - 9.56 = 0$$

$$L = -21 \text{ db}$$

$$(-9.56 \text{ loss equiv. ke} = \frac{1}{3})$$

Figures XIII(a) and (b) are curves plotted for an input SWR of 1.5 and 2.0 respectively with variable output SWR and constant G contours.

Just how much does this 21 db of cold loss reduce the gain? By direct substitution

$$G = A + B(CN) = 40 \text{ db}$$

$$CN = 2$$

$$G_{\text{no cold loss}} = -10 + 47.3(2) = 84.6 \text{ db}$$

This would indicate that the gain actually realized is 44.6 db less than that theoretically possible. This figure is a trifle high, indicating that the theoretical gain is too high. Some of this can be attributed to space charge effects which are not accounted for in theory. The rest is due to other simplifying assumptions or imperfections in actual helices not considered in theory.

The cold loss does not subtract directly from the theoretical gain. In practice a cold loss approximately equal to or greater than the desired output gain is added. Depending upon design, the gain of the

increasing wave is reduced from 1/3 to 1/2 of the cold loss.[16] Thus, if it is desired to produce a tube with an output gain of 40 it would be necessary to design a tube with 60 db gain and 40 db of cold loss added. Half of the 40 db subtracts from the gain achievable without cold loss. Thence, if in adding the cold loss too much loss is added, say an extra 10 db, the output would be reduced by 5 db.

In a previous section on dispersive helices it was stated that a tube of 30 db gain with no other loss than that of the wire (12 db) had been devised.[19] This tube was highly dispersive and does afford an answer to added cold loss. However, this paper is primarily concerned with medium dispersive tubes having a band width of at least 50% center frequency rather than the highly dispersive type having a 10% band width.

CHAPTER III

PROPOSED EXPERIMENTAL INTERRUPTED - TERMINATED HELIX

1. General description with discussion of principles.[21]

The principle suggested is briefly explained by reference to figure XIV. Instead of using a single section of helix as both "buncher" and "catcher" as Kompfner decided to do, divide the helix. Use the first section for a buncher, terminate this section and dissipate the signal at the end of the helix. Use the modulated beam to convey the intelligence to the second section of the helix. Obtain isolation between the two sections by an open circuit. This will decrease the tendency to oscillate since the gain for either section will not be as great as a similar undivided tube. Hence, the coupler need not be as perfect as required by a conventional tube. Or, taking a different view, the feedback path is reduced. The second section of the helix is also terminated at the junction with the first section. This will absorb energy reflected from the output coupler, further decreasing oscillations.

The advantages of such a procedure are evident. First, higher gain should be realized from a tube of given length. Less dissipation should be necessary since now the oscillation is materially reduced by the division of gain. Finally, the amount of loss incorporated in the termination may be allowed to vary over wide limits. The only limitation is that it remain great enough to absorb the energy in the first section and the reflected energy in the second section.

First, let us see how much increase in gain can be realized. Pierce calculates the loss incurred by severing a helix with near zero separation to be -3.52 db.[16] This is lost because no $\bar{E}$ field is present for beam

interaction until the beam induces a signal on the helix again. Therefore, the increase in gain of a conventional tube would be $\left(\frac{\text{cold loss}}{2} - 3.52\right)$ db, which in an average 30 db gain tube would amount to 12 db.

The power dissipation in cold loss in a conventional tube will now be approximated. For example, assume a power output of 1 watt, gain of 30 db. Since the cold loss is half effective on the forward gain, a gain of 45 db would have been realized without it, giving a total output of 1.75 watts. Whether or not the added loss dissipates .75 watts or a lesser figure is not certain but experimental evidence indicates a substantial amount is dissipated. In addition to this, the 1 watt output if extracted by a coupler whose ke is 1/3, will have 1/9 watt reflected which must be absorbed in the added loss if oscillations are to be prevented. In the divided helix, (assuming 17 db of gain in each section) since the signal started at .001 watt it will be at a .050 watt level at the first termination. In the second helix the 1/9 watt must be dissipated. It is quite apparent that this dissipation is materially less than .75 watt.

On the third point, little concrete can be said concerning the variation in measured cold loss. If 30 db of isolation between sections is sufficient, it little matters if the final manufacturing processes change the measured loss from 60 db to 31 db or to 80 db. Little effect on performance should be noticed. This is not the case in the conventional tube where losses directly affect output gain.

2. Experimental data.[21]

a. The experimental work of this problem was done entirely on helices designed to specifications of $\gamma a = 1.5$, $V_o = 1260$ volts.

Therefore,

$$v = \frac{V_o^{1/2} c}{506} = \frac{34.6\ c}{506} = .0703c$$

This v does not take into account the decrease due to proximity of glass. Experience has indicated that with an average clearance fit of glass on helix that v glass present = .75v.

Hence v (design to allow for glass present) = .0937 c or c = 10.65 v

$$a = \frac{(\pi a)\ v}{\omega} = \frac{1.5\ (.0937)\ c}{2\ \pi\ 3 \times 10^9} = .224 \text{ cm.}$$

$$\text{mean diameter} = \frac{2 \times .224}{2.54} = .176''$$

$$\frac{\text{circumference}}{c} = \text{time} = \frac{\text{axial distance}}{v}$$

$$\frac{\pi\ d\ v}{c} = \text{axial distance between turns}$$

$$\pi .176 \times .125 = .0693''$$

turns per inch = 14.4

The experimental helices were wound 14 turns per inch because fractional turns gearing was not available on the lathe.

b. Termination problem.

The problem of properly terminating a helix begins with the input and output matching couplers. If perfect matching couplers could be devised, the oscillation problem would not exist. For comparison, generally the merits of a coupler are stated not as the coefficient of reflection but rather as the standing wave ratio measured on a standard 51.5 ohm slotted line at the coaxial line to coupler junction. At the present state of the art, couplers which give a 1.3 SWR over a frequency band of 200 megacycles centered at 1000 megacycles can be constructed. Likewise couplers can be built which match with a 1.7 SWR over a band of 2000 megacycles at

a center frequency of 3000 megacycles. In general, the higher the center frequency, the poorer the best attainable match.

The type couplers used in this work are shown in figure XV. At first the stub was 1 1/16" long, slightly greater than a quarter wavelength at center frequency. The molybdenum sleeve and interior of the stub may be considered a coaxial transmission line. Thus the open circuit at (B) appears as a short circuit at (A). Likewise, the large area of the molybdenum cylinder appears as a large capacitance acting as a low impedance r. f. bypass for signal frequencies. Thus, the cylinder is anchored to the coupler and fixes one end of the pick up antenna so that it may be fed. It was found that by reducing the stub length to 3/4" and using a tapered sleeve length of 3/4", better results could be obtained. The couplers were tuned by use of a frequency swept klystron oscillator with a directional coupler and scope presentation of frequency vs reflection magnitude. This was rapid and enabled the best compromise overall match.

Now the main problem of terminating the interruption in the helix will be discussed. There are at least three possibilities:

(1) The helix may be terminated in a spiral similar to a helical antenna which may be encased in the glass envelope.

(2) The helix wire may be brought out through the envelope at some location along the tube. By proper impedance matching techniques and correct restraining configuration, it may be connected into a dissipative load.

(3) The helix may be wound back upon itself similar to a coupled helix and the loss incorporated in the back wound helix.

This paper will be restricted to experimental work done on (1). Investigation revealed that (2) had already been undertaken with none too successful results. (3) is an extention of (1), having more difficult restraining problems than (1) plus the coupled helices principle. It appeared that (1) would be more simple than (3).

The construction of the helices was done in the conventional manner, by winding on a mandrel in a machine lathe. The mandrel was inserted into a cone at one end. The cone had a thread machined on it. A variety of types of wire, tungsten, copperplated tungsten, and molybdenum in .020" and .030", was used. Nearly all helices were eventually wound from molybdenum. It lacked the rigidity of tungsten but also was not nearly so brittle. Tungsten was highly desirable from a point of view of retaining exact shape. However, the helix and spiral was first wound and fired to set; then the spiral was pressed and fired again to set flat; then if the spiral was irregular, it was fitted into a flat threaded steel form and fired for a third time. Attempts to combine the second and third operations with tungsten failed due to spring qualities preventing it from being compressed into the face plate thread. The repeated firings made the tungsten so brittle it precluded the possibility of its use.

The first check made was to see if the cone shaped spiral, prior to being pressed, would constrain the wave and if it could be loaded as a dissipative termination. This was a simple, less difficult configuration than the flat spiral. It was believed any results would be applicable to the flat spiral with certain reservations and modifications. A 15° central angle cone with 9 turns per inch (measured along the axis) 2 inches long was first tested.

It might be well at this point to describe the set-up for measuring SWR along the helix. This was to serve as a criterion of how well the helix was terminated. The coupler was secured in a split brass pipe of 1 3/4" diameter by a hose clamp which could be loosened to enable adjusting for a match. The belled end of the glass envelope was held firmly by a teflon disk which was clamped in the brass shell. The entire shell was clamped to a 3/8" flat sheet of metal which was very rigid. Mounted on the metal sheet was a carriage which had a distance scale calibrated in centimeters. The carriage height was adjustable by four screws so it could be leveled up and the attached pick-up probe set at a desired distance from the glass envelope.

The SWR measurement along the helix was quite a difficult problem. Basically, a single slow wave traverses the helix. However, an essentially unguided free space wave is present also. The latter may be reduced to a very small amplitude by appropriate launching and care in terminating the spiral waves. Another way of eliminating the "fast" wave is by placing the helix inside a pipe too small to support other waveguide type modes. In this case it would have meant a pipe 1/2" in diameter. However, it would have been necessary to split the pipe to enable the introduction of a probe. Appropriate launching was tried. Care in terminating the spiral waves was only possible when the spiral was a good match. When the spiral properly terminated the helix, a small SWR was observed which was regular along the helix. When it did not, a very irregular wave was observed. This could be attributed to the presence of a "fast" wave, parasitic modes, and multiple partial reflections. It was found that a very small loop probe

worked best. It picked up the desired wave and largely excluded the undesirable. A round circular probe which completely encircled the helix envelope was partially successful. A pointed probe was constructed; also a shielded factory-manufactured point probe with a tuning stub was tried but finally only the small loop was used for the bulk of the measurements. It was also found that the closer to the glass envelope the probe was placed, the better the ratio of $\frac{\text{desired wave}}{\text{undesired waves}}$. At first approach it would seem that the best measurements would be at the edge of the fields so as not to distort the lines of force. However, the desired wave was found to decrease in strength in an exponential manner where as the parasitics decreased linearly. In general, the complex wave pattern problem was most unfortunate. Due to the irregularities of consecutive maxima and minima when a high SWR existed, no definite SWR could be set for a given frequency in case of SWR>1.5. This eliminated the very valuable process of comparing high helix SWR's and determining when improvement in termination existed.

Now a helix with a tapered spiral termination shaped as removed from the cone was first tested with no losses whatsoever incorporated. Three isolated frequencies were observed where low SWR existed in the 2000 to 4000 megacycles band.

Then an attempt was made to load the spiral. Aquadag was coated on the outside of the glass envelope from the helix junction about half way to the end. It was also painted on the inside from the end of spiral toward the helix, overlapping slightly the coating on the outside. This was not successful, due primarily to inability to apply aquadag smoothly with

a brush because the aquadag may have been the wrong thickness. Eventually, the interior aquadag was removed and replaced by five evenly spaced longitudinal slabs of mica approximately 1 1/2" long, .14" wide and .004" thick. The sprayed aquadag measured 200 ohms per square and was placed with the unpainted mica side toward the spiral. It effectively loaded the spiral very well. A low SWR, below 1.15 was measured along the helix from 2400 megacycles to 4000 megacycles. A similar helix with a spiral of 4 turns per inch (along axis) was tested. It yielded a low SWR along the helix from 4000 down to 2800 megacycles.

With this representative information in hand, the spirals were pressed flat and fired to set. Then to further insure uniformity of the spirals, they were fitted into threaded steel blocks, clamped in place, and fired.

Now the helices with flat spiral terminations were tested. It was found that, with very careful loading, a SWR of 1.15 or under was observed on the closely spaced spiral from 2000 megacycles to 2900 megacycles. The aquadag loading had to be extremely thin and as close to the spiral as possible, i. e., .0005". The required close proximity was indicative that with this tight spiral the fields are very close to the wire. Perhaps if it were possible to pot the outer turns in a lossy ceramic the high end could have been matched. On the widely spaced spiral with loading a distance of .002" an excellent match with a 1.05 or under SWR on the helix was achieved from 3100 megacycles to 4000 megacycles.

A threaded cone was machined for a compromise 7 turns per inch (axially) and a helix and spiral prepared. After experimenting with the

junction between the helix and spiral, a successful match was achieved from 2000 to 3400 megacycles. Again however, the loading was very close to the spiral. It is further believed that the real answer to the particular problem is a 6 turn per inch (axially) 15° cone pressed into a flat spiral with aquadag loading of 500 ohms per square at a distance of .001" or closer.

In passing, a word should be said concerning the junction between the helix and spiral. Effort was made to vary this, keeping a constant γa and rounding the place the helix evolved into a spiral. In the last elements produced, good results were obtained by having the last turn of the normal helix diameter enter the flat spiral at the normal pitch and from thence transform into a flat spiral. This is a desirable form since the minimum helix separation is desired to prevent debunching of the beam.

c. Isolation problem.(21)

Considerable experimental work was done in attempting to obtain a high degree of isolation between the two helices. Previous measurements by Mr. George Mather, of Stanford University Electronic Research Laboratory indicated that a simple severed helix in a glass envelope must have a separation of 1/2" to achieve an isolation of 40 db. A similar test indicated that if the glass envelope was expanded at the separation of the helices that 1/4" would give 30 db of isolation.

In the case with the spirals facing each other, without effective loading, separated by .005", approximately 25 db of isolation was observed. The reason for the higher than expected figure was due to the helices being of opposite thread.(3) However, because the spirals were not matched

and loaded, only 25 db was measured. A copper circular disk, with a hole to permit passage of the beam, was interposed and welded to the input end. This resulted in 60 db of isolation. However, in the final stages, when the spirals were matched and loaded, the isolation measurement was rechecked without an intervening copper disk. A value of 50 db was observed. This further substantiated the contention that the energy was being dissipated in the terminations. For a sketch of final product, see figure XVI.

In closing it might be said that no doubt technical difficulties may appear in the construction of this tube. At present it appears from cold measurements to show considerable promise. There are undoubtedly new difficulties which would arise in a tube with a beam. However, it is believed that the principle is basically sound and indicative of meriting additional research.

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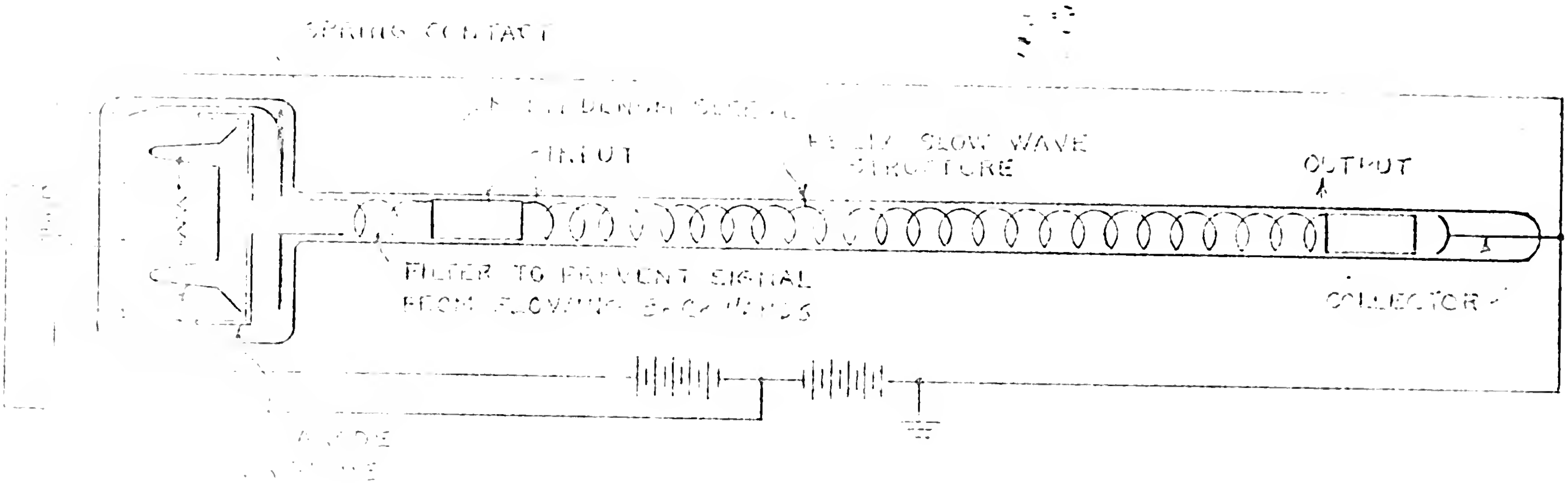


FIGURE I BASIC COMPONENTS OF TRAVELING WAVE TUBE.

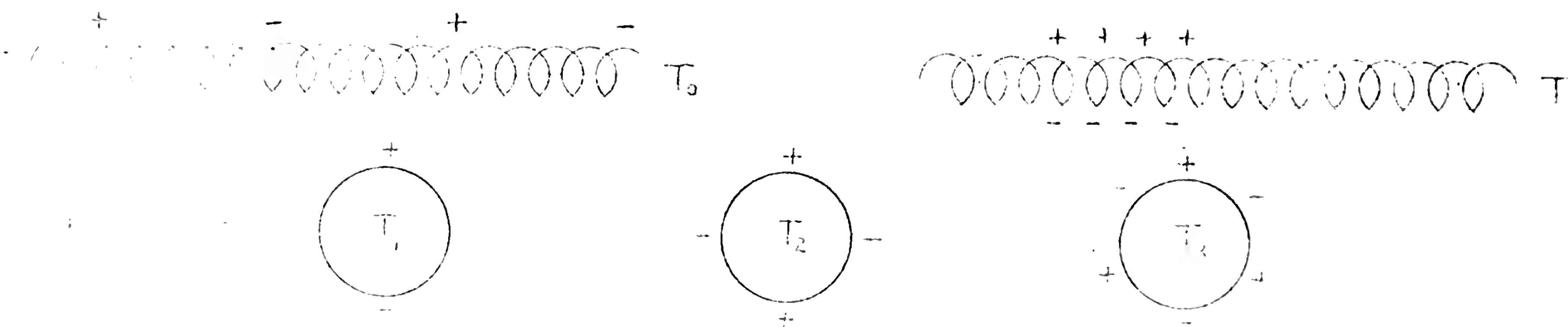
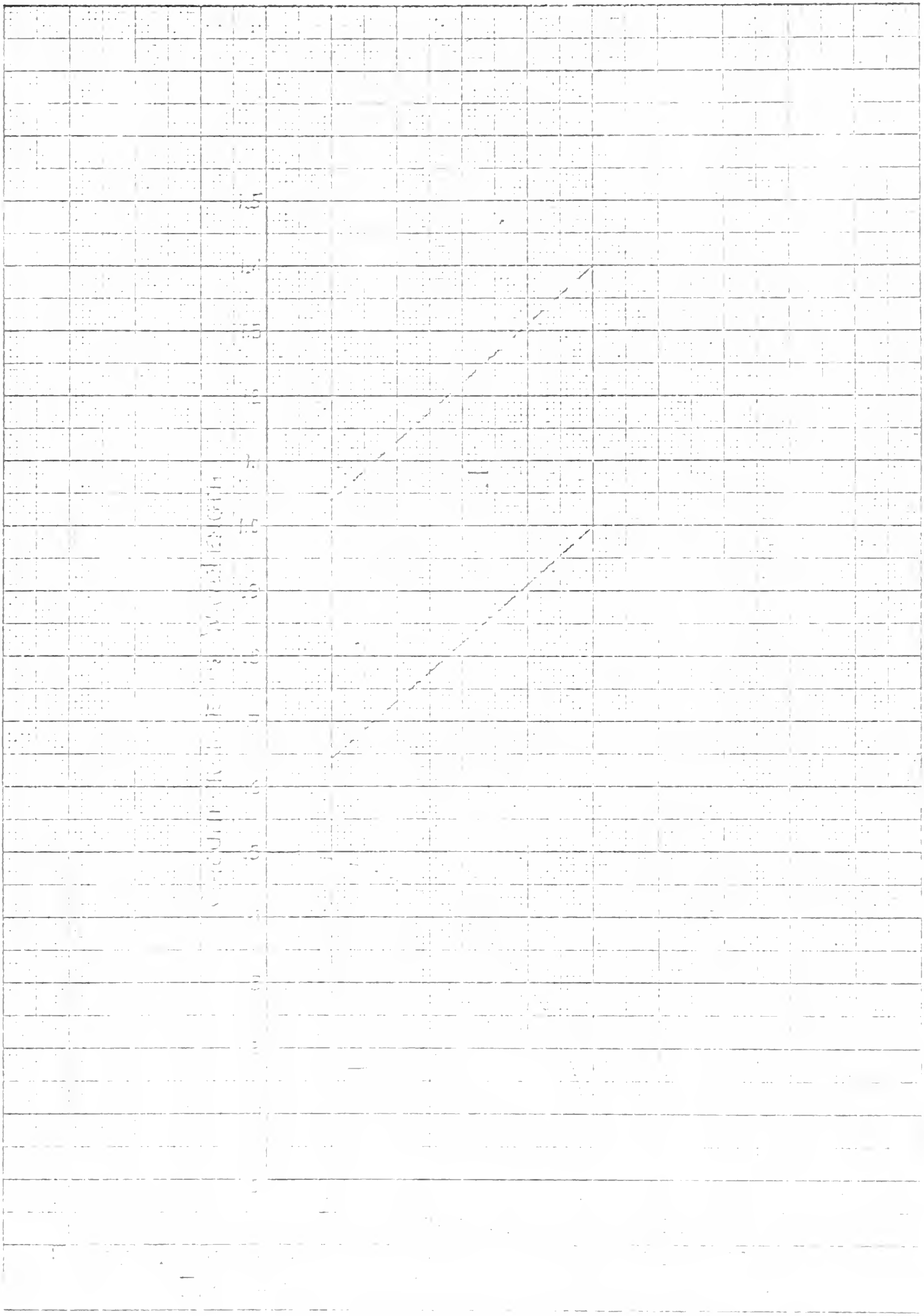


FIGURE II INSTANTANEOUS CHARGE DISTRIBUTIONS FOR SIMPLE TRANSMISSION MODES



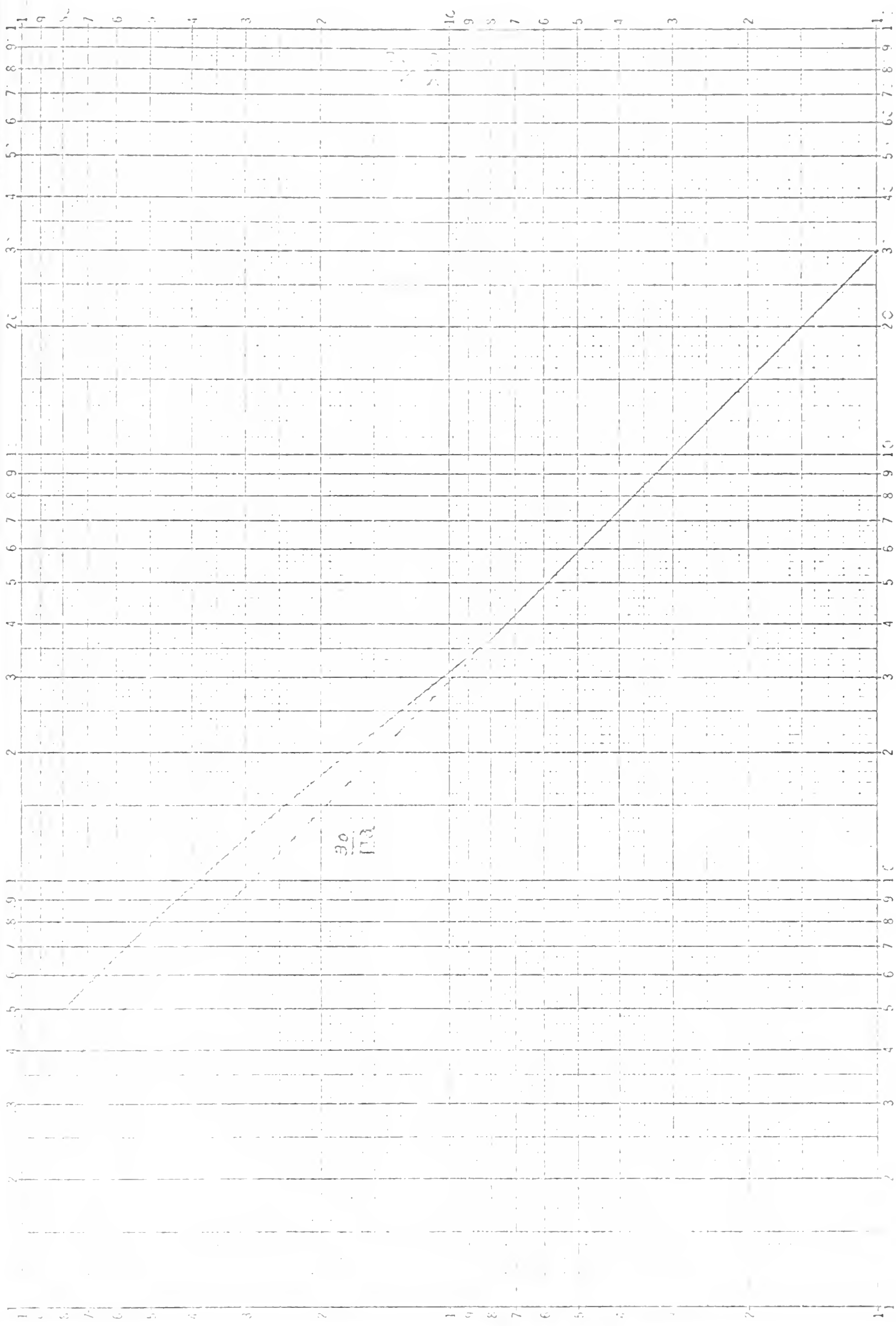
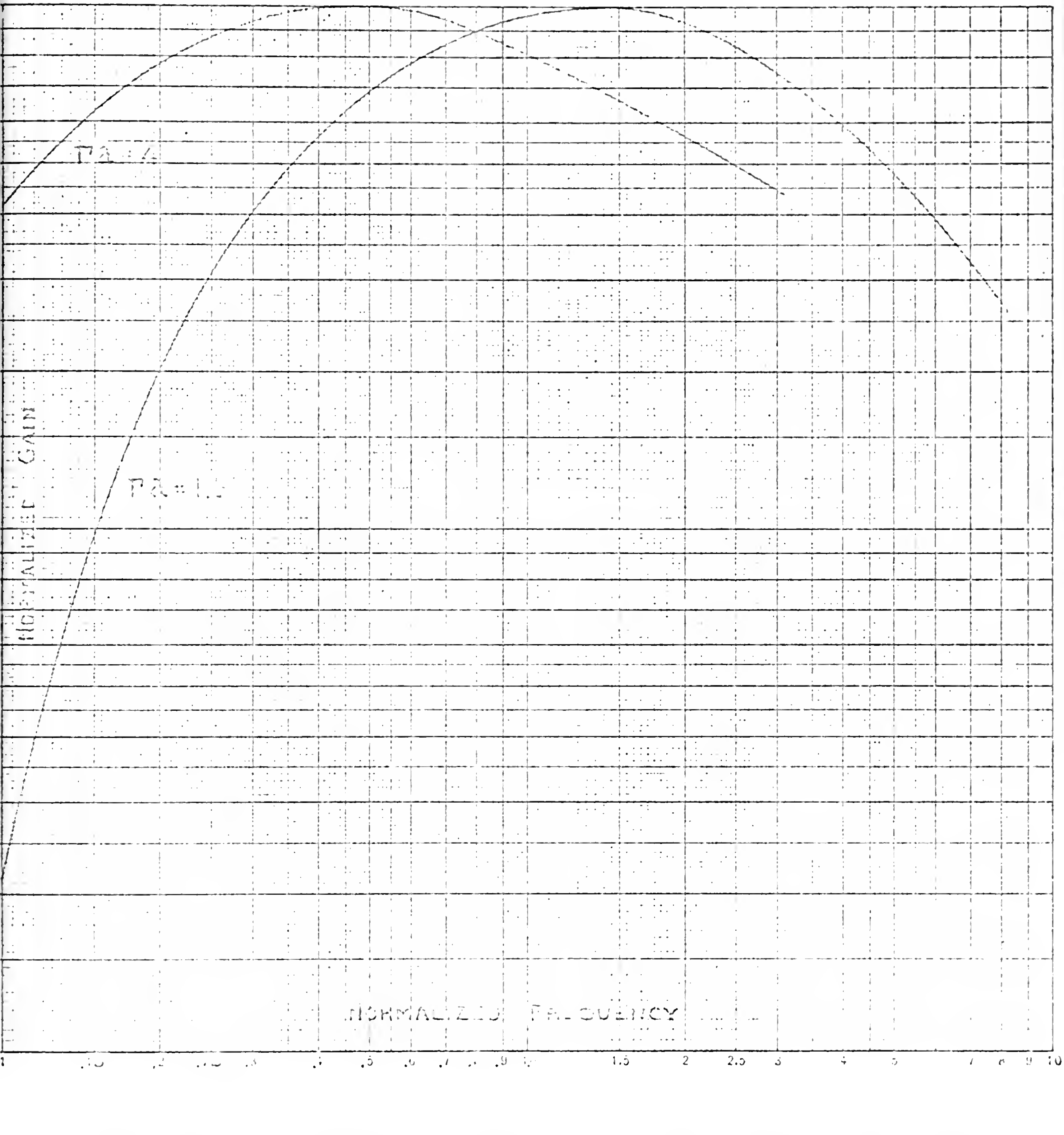
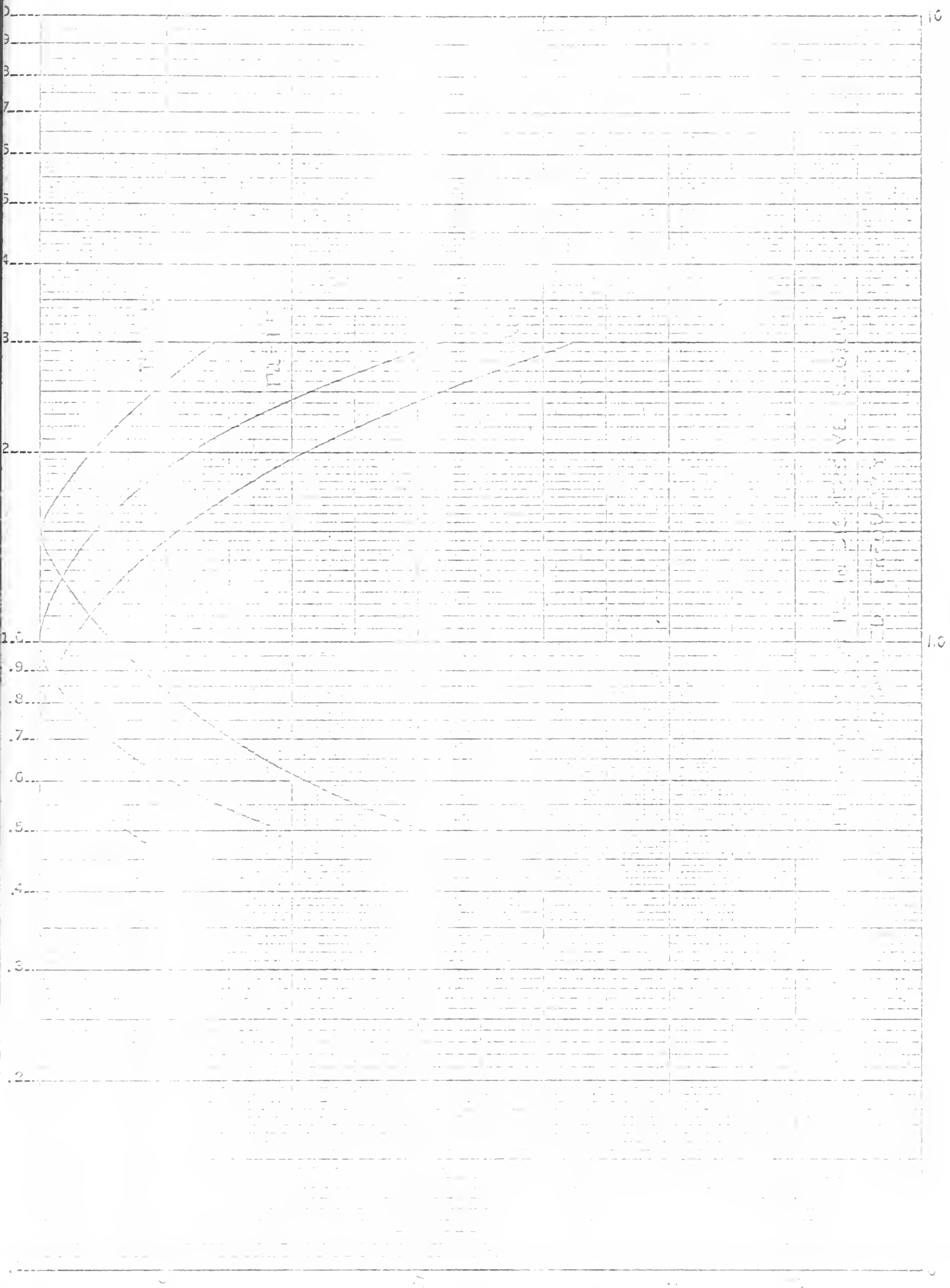


FIGURE IV TRANSVERSE HELIX IMPEDANCE



AND SMALL

VALUES OF T'α


10
2
1.0
.9
.8
.7
.6
.5
.4
.3
.2

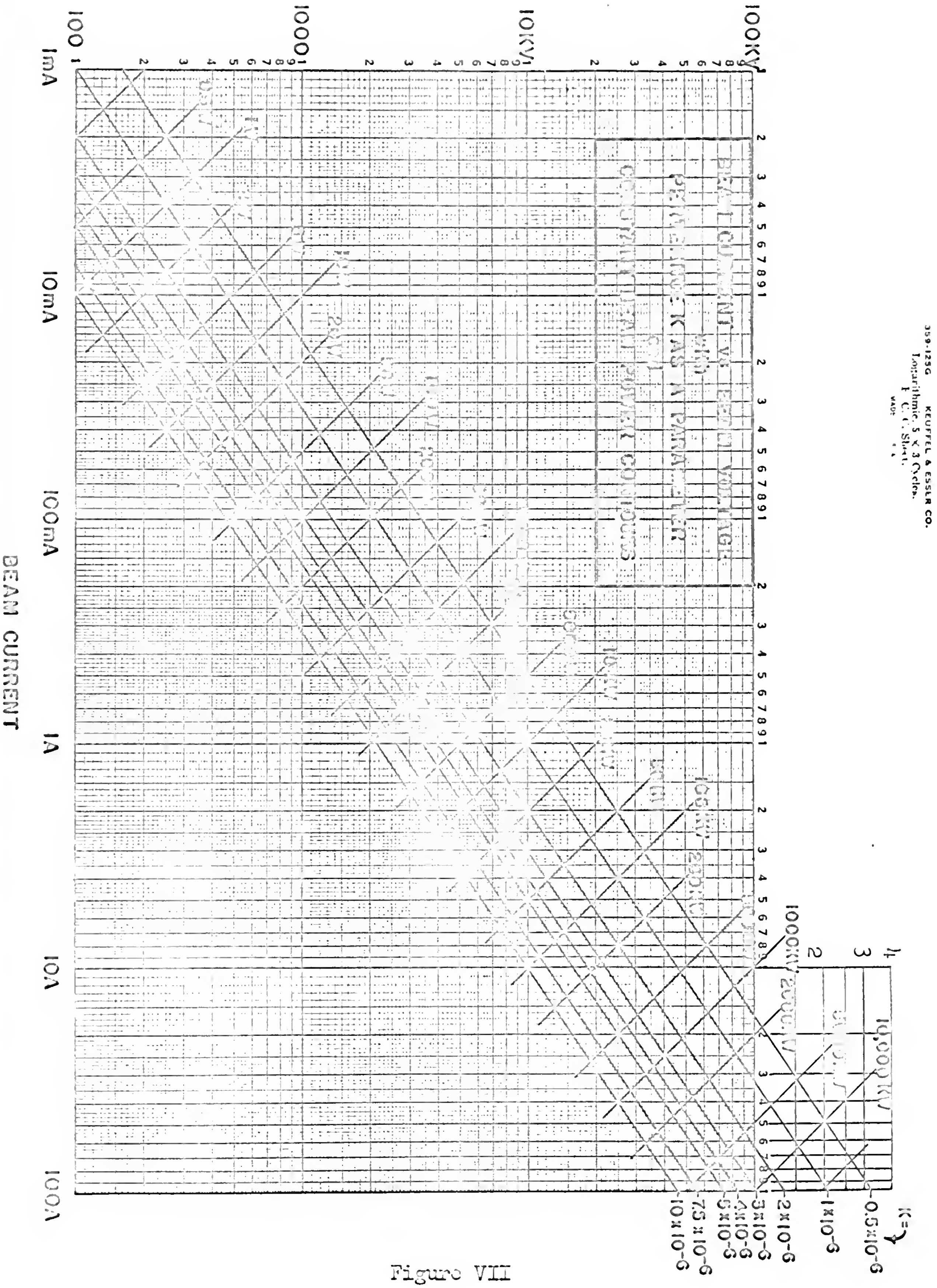
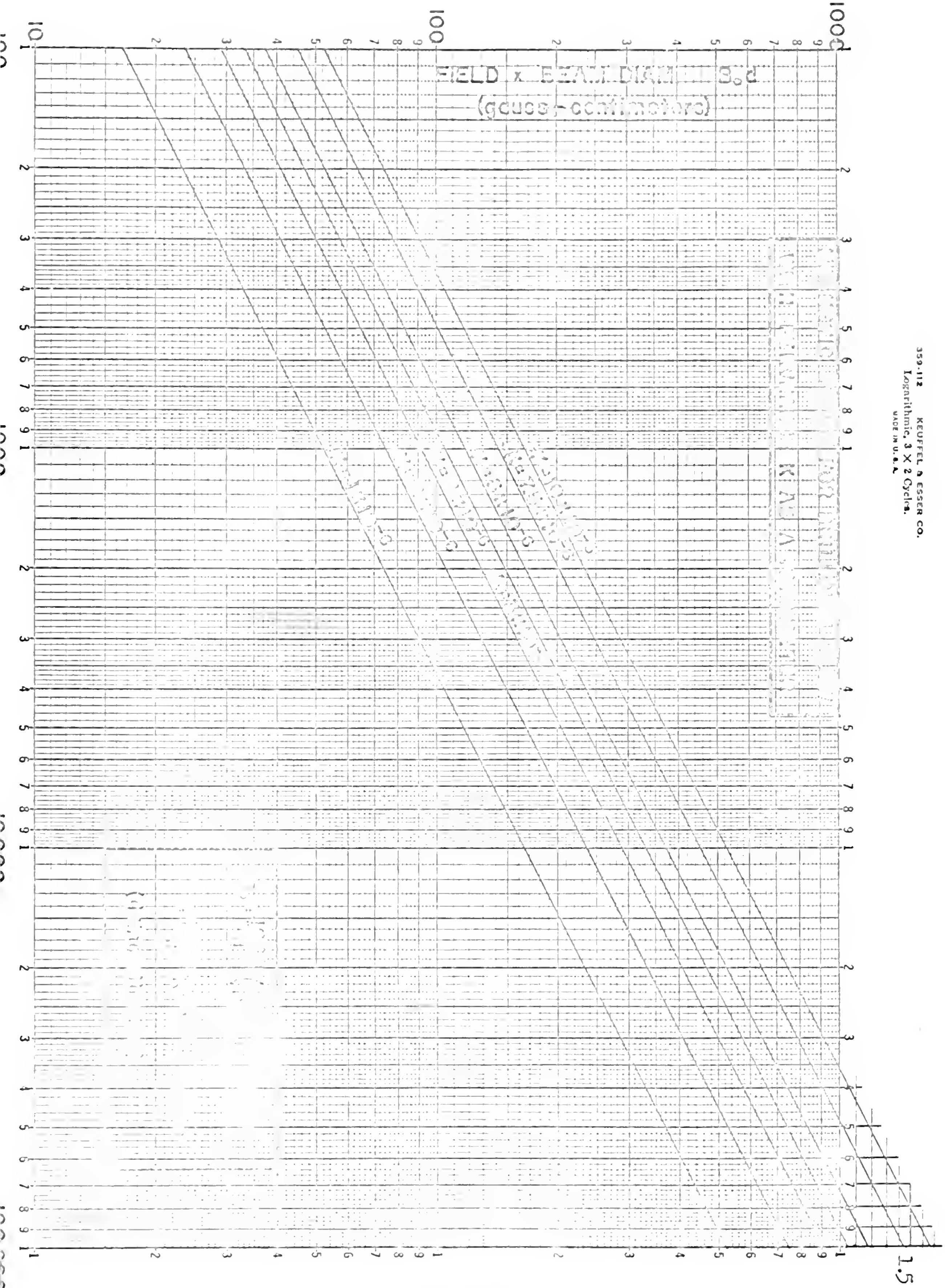

100KV
10KV
1000
100
1mA
10mA
100mA
1A
10A
100A
BEAM CURRENT
1000KV
K=
0.5x10-6
1x10-6
2x10-6
3x10-6
4x10-6
5x10-6
7.5x10-6
10x10-6

Figure VII



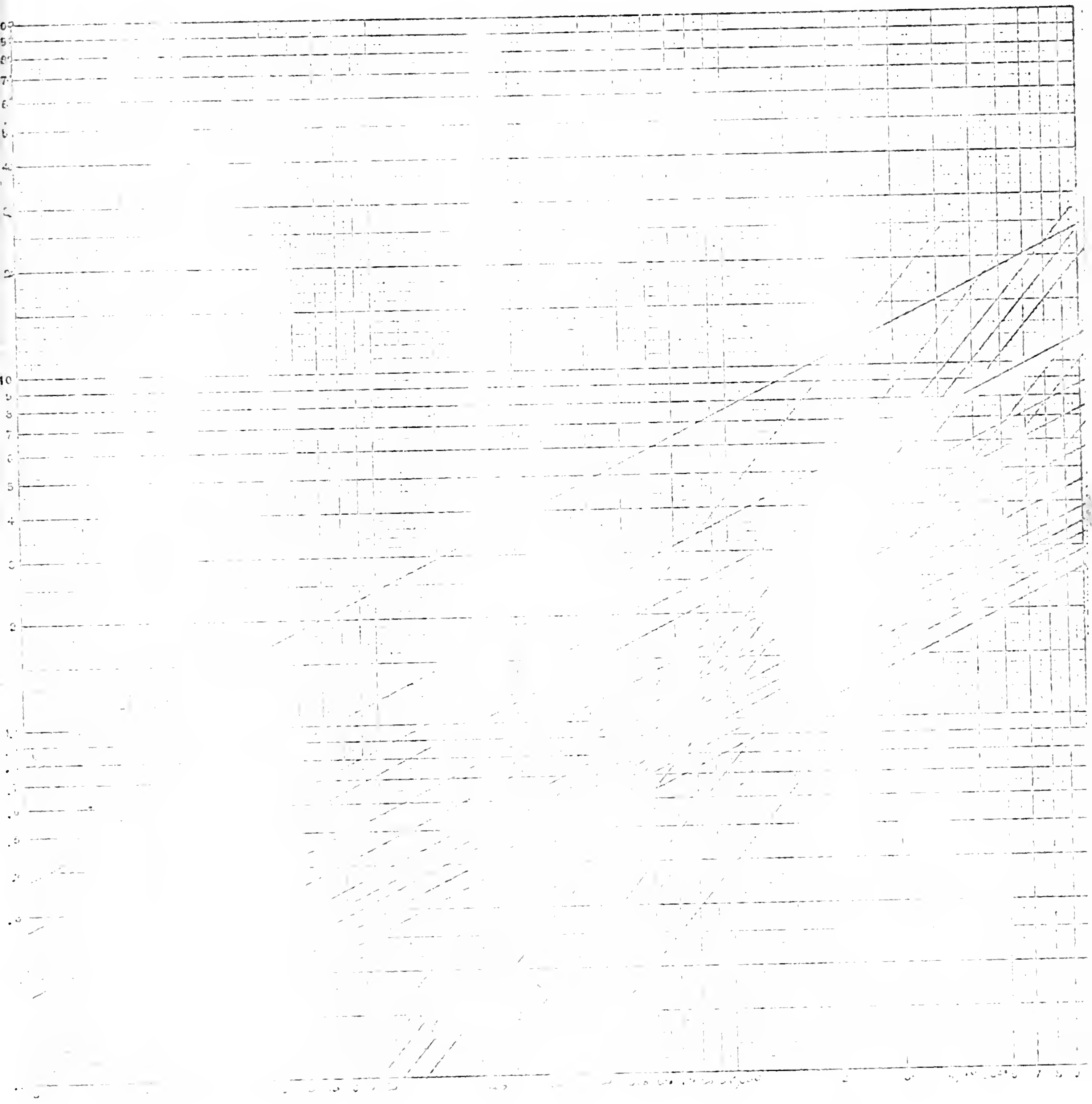
(gauss-centimeters)
359-112 KEUFFEL & ESSER CO.
Logarithmic, 3 X 2 Cycles.
MADE IN U.S.A.
1.5

Figure VIII

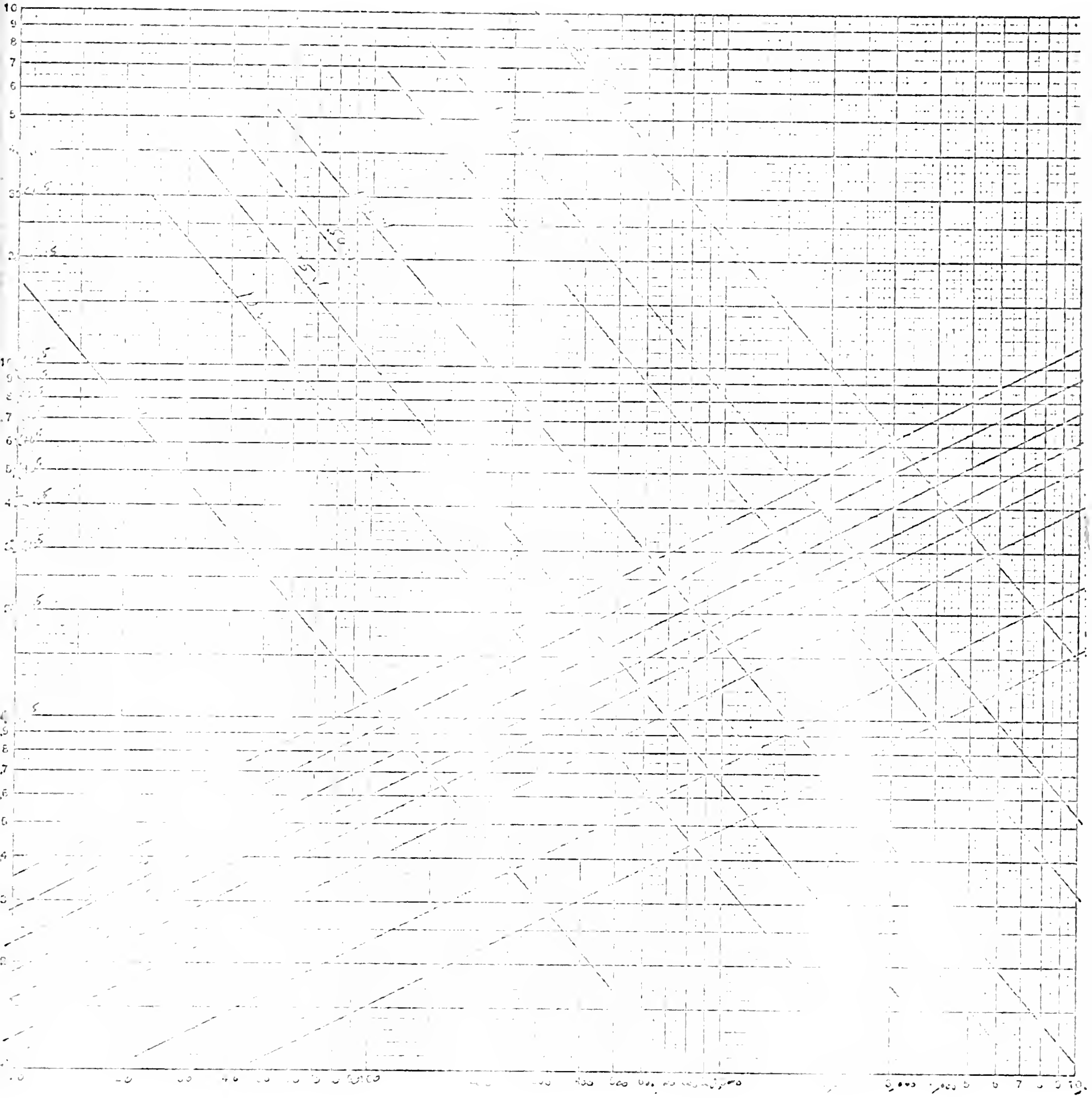
MAGNETIC FIELD FOR BRILLOUIN FLOW VS BEAM VOLTAGE WITH CONSTANT BEAM POWER AND CONSTANT PERVEANCE CONTOURS

HELIX LENGTH VS BEAM VOLTAGE AND GAIN

WITH CONSTANT BEAM POWER AND CONSTANT PERVEANCE CONTOURS



B^2L Vs Beam Voltage and Gain with Constant Beam Power and Constant Perveance Contour



Beam Voltage

Volts

Figure III

16

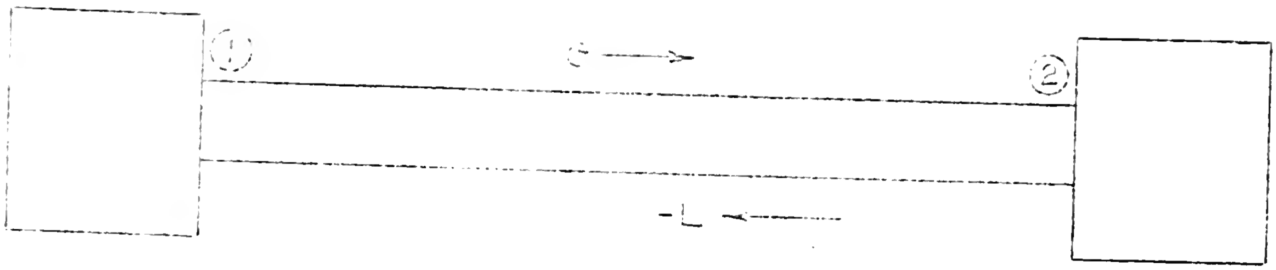


FIG XII DIAGRAM FOR COMPUTING NECESSARY COLD LOSS

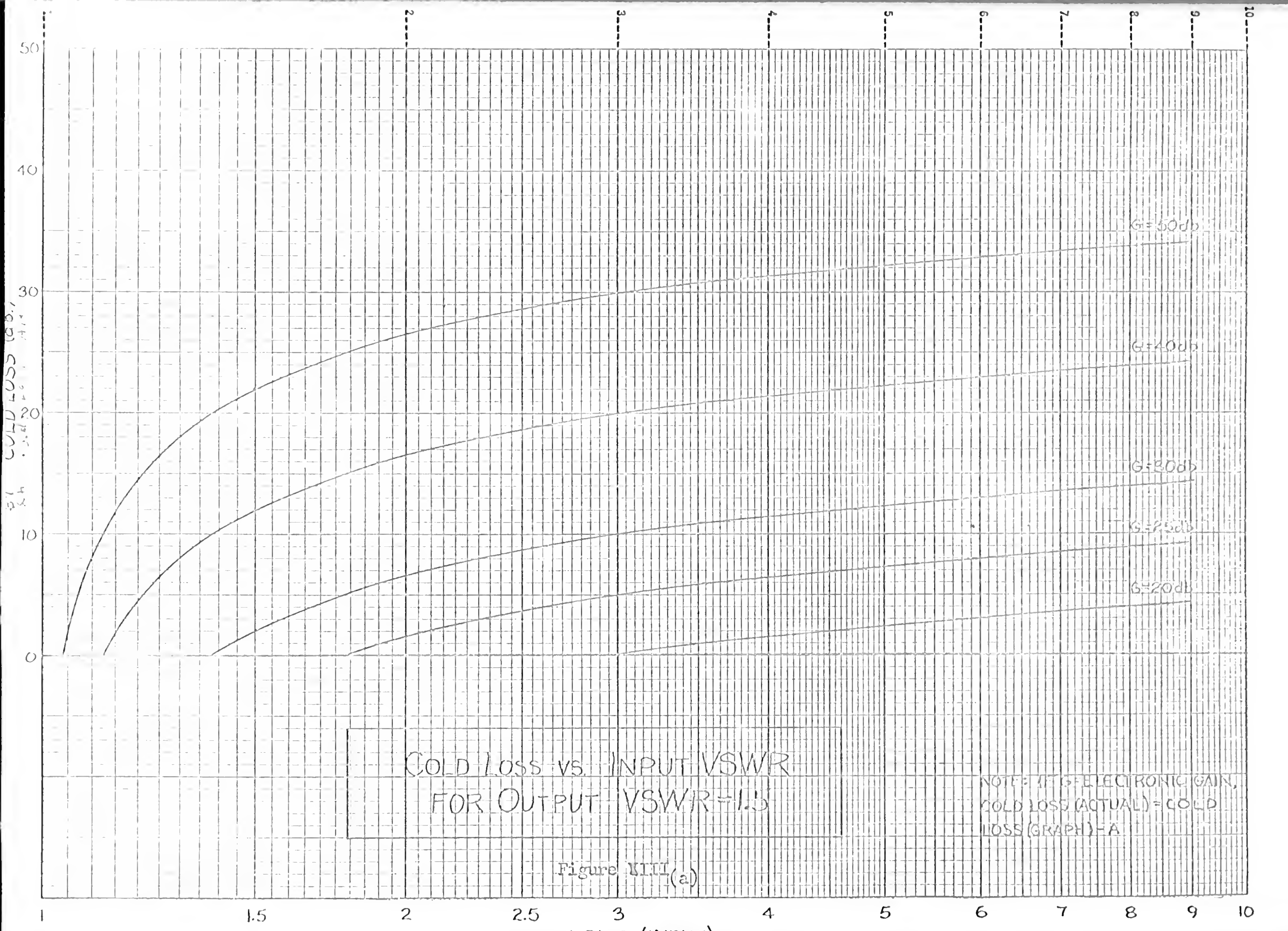


Figure XIII(a)

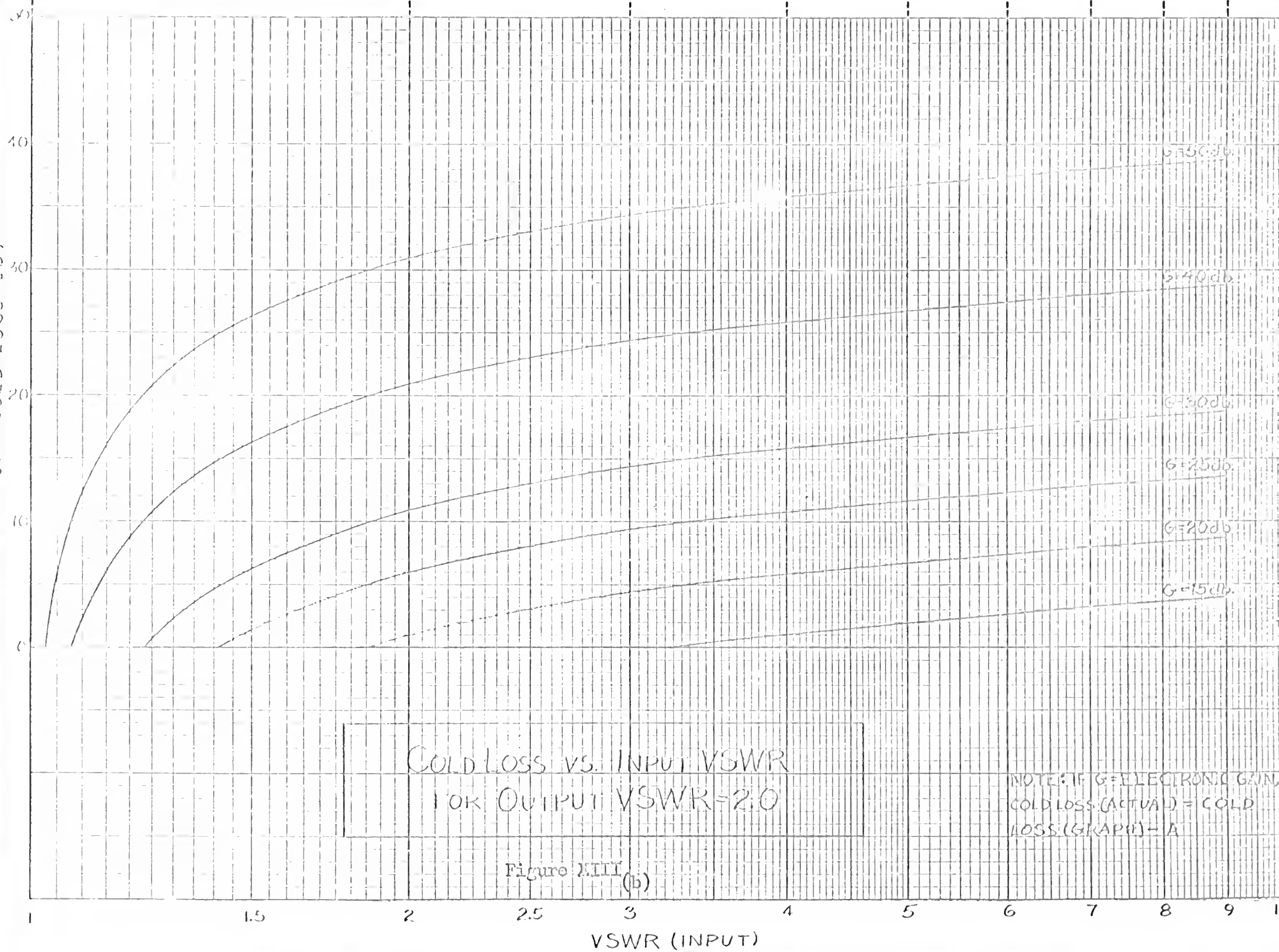


Figure XIII(b)

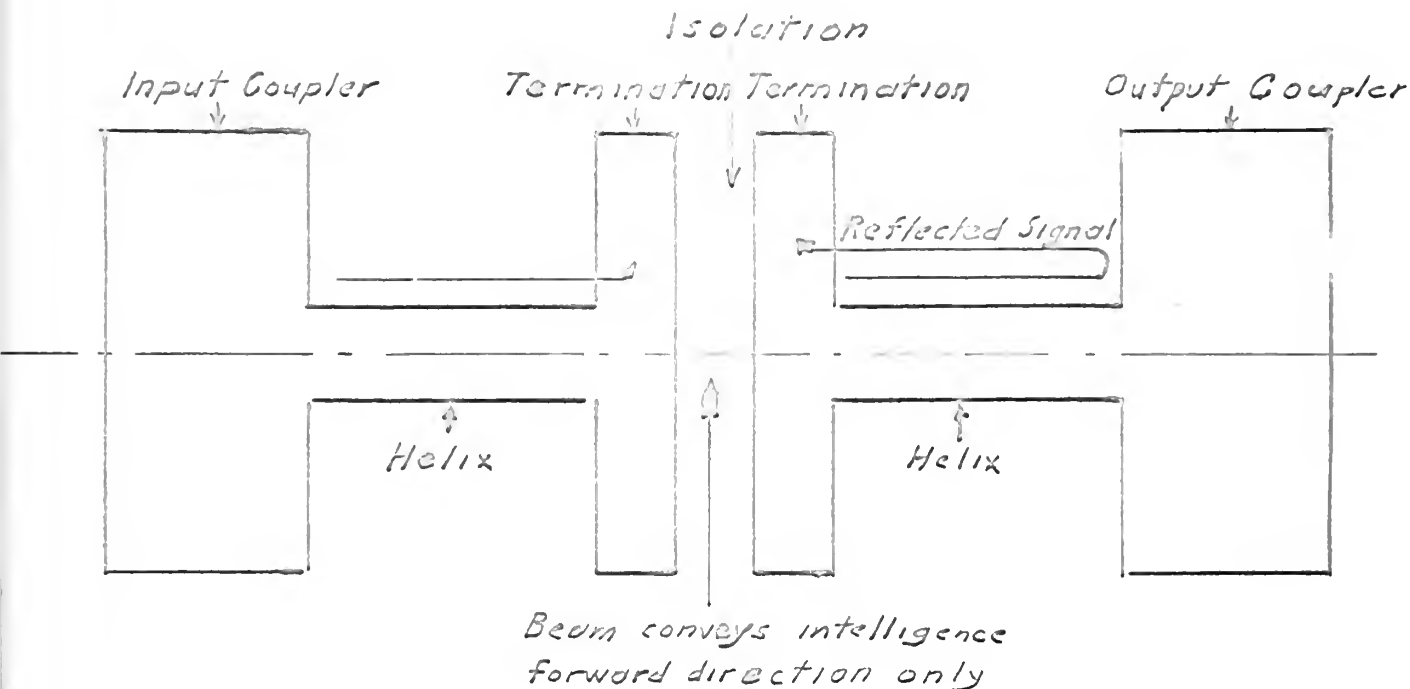


FIGURE XIV PROPOSED PRINCIPLE FOR INTERRUPTED-TERMINATED HELIX

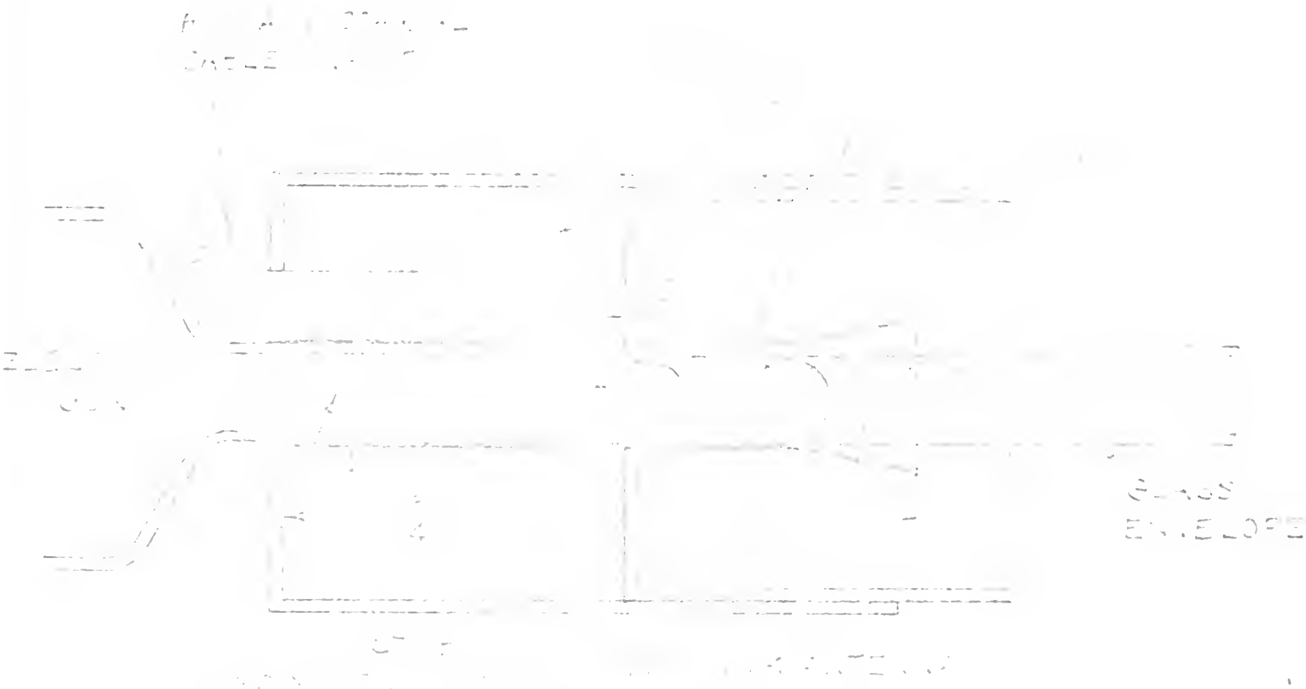


FIG. XVI

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C97 Cutchall
c.2 Traveling-wave
amplifiers.